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NEAR-END CROSSTALK NOISE MINIMIZATION AND POWER REDUCTION FOR DIGITAL SUBSCRIBER LOOPS

CROSS-REFERENCE TO RELATED APPLICATION

[1] The present application is related to commonly-assigned, co-pending, application for patent Serial No. _____ entitled "METHOD AND APPARATUS FOR APPLICATION

5 DRIVEN ADAPTIVE DUPLEXING OF DIGITAL SUBSCRIBER LOOPS" filed concurrently herewith, the disclosure of which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

Technical Field of the Invention

10 [2] The present invention relates to digital subscriber loop (DSL) systems and, more particularly, to a method and

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apparatus for minimizing near-end crosstalk (NEXT) noise and reducing power consumption within a DSL system modem, transmitter and line driver.

Description of Related Art

5   [3]   Crosstalk is noise that is present on a phone line due to the electromagnetic radiation of other, closely proximate, phone lines (for example, lines located in the same cable bundle). The term "crosstalk" was originally coined to indicate the presence in a telephone receiver of

10   unwanted speech sounds from another telephone conversation. The term has been gradually broadened in application to refer to interference between any kind of communications circuits. This kind of noise includes both near-end crosstalk (NEXT) and far-end crosstalk (FEXT) components.

15   [4]   With respect to digital subscriber loop (DSL) systems, it is generally accepted that the NEXT noise, as opposed to FEXT noise, presents the major source of interference. The reason for this is that FEXT noise passes through the entire DSL loop and thus its propagation loss generally is

20   very large and in many cases the noise can simply be ignored. The opposite is true with respect to NEXT noise which undergoes little, relatively speaking, attenuation

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in its short propagation path. The concerns over NEXT noise remain even when the bit rate of the transmitted signal is small because idle ATM cells are inserted to fill up all the data frames of the DSL link (both upstream and

5   downstream), and the transmission of this filler material is also a source of noise.

[5]   When DSL services are offered on different loops in the same cable bundle, it is very important to reduce and minimize NEXT noise contributed by a DSL communication on

10   one loop with respect to the communications on other loops within the bundle. Doing so beneficially improves DSL system error rate performance and increases loop throughput.

[6]   Power consumption is also a very important factor to

15   be managed in DSL systems. This is most commonly an issue raised with respect to the design of the DSL modem, and it applies to both the customer premises equipment (CPE) location and the central office (CO) location. A number of power concerns are recognized in the art. For example,

20   the more power that is transmitted in a DSL system, the more likely it is that crosstalk noise will be coupled to other DSL users in the same cable bundle. It is also

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recognized that if a universal serial bus (USB) interface is used for an external modem at the CPE side, the power consumption of the modem is limited by the USB standard. With respect to the CO location, many DSL line cards are

5 installed in a very limited space, and heat dissipation is a serious concern. Any reduction in power consumption in the DSL modem is therefore welcomed. Still further, power consumption is also important for laptop computers having limited capacity batteries. Finally, the use of additional

10 bandwidth by the filler material ATM idle cells (which may lead to NEXT noise as discussed above) increases the power consumption for both of the line drivers at the CO and CPE locations without providing a substantive communications benefit.

15 SUMMARY OF THE INVENTION

[7] The present invention concerns a method and apparatus associated with a digital subscriber line (DSL) transmitter that optimizes communications performance over a cable bundle carrying at least one active DSL loop communication.

20 In response to a new DSL loop communication, a required bit rate for that communication is determined. That required

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bit rate corresponds with a required bandwidth for the new DSL communication that is generally smaller than a total available bandwidth on the loop. A calculation is then made of a crosstalk noise effect caused by the new DSL loop

5   communication with respect to the at least one active DSL loop communication. This calculation is made for each one of a plurality of potential positions for the required bandwidth within the total available bandwidth. The potential position having the best calculated crosstalk

10   noise effect is then selected as the position of the required bandwidth for carrying the new DSL communication.

[8] More specifically, and in accordance with an embodiment of the present invention, the required bandwidth corresponds to a certain number of DMT subcarriers, and it

15   is those subcarriers that are used to transmit the new DSL communication. These subcarriers may vary in number with different potential positions of the required bandwidth within the total available bandwidth.

[9] It is an embodiment of the present invention, with

20   respect to the process used in choosing the position of the required bandwidth, for that process to be applicable to both upstream and downstream available bandwidths.

[10]   It is still further an embodiment of the present invention for the determination of the required bit rate of the new DSL loop communication to comprise that bit rate which is needed for data communication without the inclusion of unnecessary idle ATM cells.

[11]   By choosing a possible position for the required bandwidth within the total available bandwidth where the calculated crosstalk noise effect with respect to the at least one active DSL loop is minimized, an optimized performance for the DSL modem may be achieved. Furthermore, the use of a minimum number of DMT subcarriers in association with the required bandwidth effectuates a reduction in line driver power consumption as compared to the prior art.

BRIEF DESCRIPTION OF THE DRAWINGS

[12] A more complete understanding of the method and apparatus of the present invention may be acquired by reference to the following Detailed Description when taken in conjunction with the accompanying Drawings wherein:

[13] FIGURE 1 is a functional block diagram of an ATU-R transmitter for a general DSL modem;

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[14] FIGURE 2 is a functional block diagram of an ATU-C transmitter for a general DSL modem;

[15] FIGURE 3 is a diagram illustrating NEXT noise and FEXT noise sources in a cable bundle;

5 [16] FIGURE 4 is flow diagram illustrating a process for NEXT noise minimization when establishing a new DSL link;

[17] FIGURE 5 is a state machine diagram operating an idle ATM cell removal process;

[18] FIGURE 6 is flow diagram illustrating a process for 10 performing an idle cell discarding operation;

[19] FIGURE 7 illustrates selective bandwidth utilization for DSL service;

[20] FIGURE 8 illustrates selective bandwidth utilization to minimize NEXT noise in a non-overlapped DSL system 15 implementation;

[21] FIGURE 9 illustrates selective bandwidth utilization to minimize NEXT noise in an overlapped DSL system implementation; and

[22]   FIGURE 10 is a flow diagram for a process to 20 minimize NEXT noise for the new initialized loop in the same cable bundle.

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DETAILED DESCRIPTION OF THE DRAWINGS

[23] Reference is now made to FIGURE 3 wherein there is shown a diagram illustrating near-end crosstalk (NEXT) noise and far-end crosstalk (FEXT) noise sources in a cable bundle 10. It is well known that the performance of a DSL modem is generally limited by the crosstalk noise introduced by other modems that are connected to the other loops in the same cable bundle 10. The crosstalk phenomenon can be modeled using two components, namely NEXT noise and the FEXT noise. A DSL line driver 12 is designated by a triangular "T" reference, while a DSL line receiver 14 is designated by a triangular "R" reference. A disturbing circuit 16 is shown as both a NEXT noise component source and a FEXT noise component source. NEXT noise occurs when the line receiver 14 of the disturbed circuit 20 is located at the same end of the cable bundle 10 as the line driver 12. The disturbed circuit 20 experiences NEXT noise due to electromagnetic radiation received on line (or loop) 26 from line/loop 24 in the cable bundle 10. FEXT noise occurs when the line receiver 14 of the disturbed circuit 18 is located at the other end of cable bundle 10 from the line driver 12. The disturbed

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circuit 18 experiences FEXT noise due to electromagnetic radiation received on line/loop 22 from line/loop 24. The NEXT noise component is generally of much greater magnitude and concern than the FEXT noise component.

5   [24]   In order to improve the performance of a DSL modem, one primary objective of a modem designer should be the minimization of the crosstalk noise in the cable bundle 10. This is especially true with respect to the NEXT noise component. For example, NEXT noise may be minimized in

10   prior art G.Lite and G.DMT DSL system implementations by separating the upstream and downstream bandwidths. This prior art solution, however, is of limited utility as DSL modems and communications services become more complex, and a need exists for a technique of more universal and future

15   applicability for reducing the NEXT noise component and combating power dissipation concerns.

[25] In accordance with the present invention, an optimized crosstalk performance for a DSL system may be obtained by considering the following factors:

20   [26] Minimization of the NEXT noise. The existence of overlapping upstream and/or downstream bandwidths for DSL communications by plural users on a common cable bundle is

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a primary cause of NEXT noise.   It is further recognized,
as discussed above, that not all of the available
upstream/downstream bandwidth is needed and thus a smaller,
necessary or required bandwidth may be allocated.   Some

5   control may be exercised over the placement of the required
downstream bandwidth within the DSL spectrum.   By
selectively placing the required downstream bandwidth, the
NEXT effect experienced by others on the same cable bundle
as a result of a common or overlapping bandwidth between

10 loops may be minimized, and significant reductions in NEXT
noise may be achieved.

[27] Minimization of allocated bandwidth.   DSL operation
dictates the insertion of idle ATM cells to fill all data
frames when the bit rate of the data to be transmitted is

15 smaller than the available throughput rate of the DSL link
(both upstream and downstream) that is defined by the
allocated number of subcarriers.   For example, when the DSL
user is browsing a website, the upstream data rate can be
as low as few kilobits per second, with the remainder of

20 the available throughput rate is met by the transmission
of idle ATM cells that add substantively nothing to the
data transmission but nonetheless contribute significantly

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to crosstalk noise as well as power consumption. In some
extreme situations, for example, when there is no data to
be transmitted, idle ATM cells are transmitted to fill the
available throughput rate and accordingly comprise the only

5 source of crosstalk noise. By intelligently selecting the
minimum number of the subcarriers used for the Digital
Multi-tone (DMT) signals (i.e., minimizing the utilized
bandwidth) according to the bit rates of the data streams
in the upstream and downstream directions, the size of the

10 DSL link bandwidth used for communication is better
tailored to the data being transmitted and crosstalk noise
to other users, especially NEXT noise, can be significantly
reduced. As an added benefit, by controlling the usage of
the upstream and downstream bandwidth in terms of the

15 minimum number of allocated and utilized DMT subcarriers,
the power consumption of the line driver is substantially
reduced.

[28] Attention is now directed to FIGURE 4 which is a flow
diagram illustrating a process for NEXT noise minimization

20 when establishing a new DSL loop communication. In step
90, the required bit rate for the data communication
(upstream and/or downstream) over the new DSL loop

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communication is determined. More specifically, the data communication is examined to identify and remove idle ATM cells. What is left over substantially represents the bit rate requirements for transmission of the data

5   communication itself.

[29] An idle ATM cell removal process performed in connection with step 90 permits the identification ATM cell boundaries in the payload of the data communication. The cells within the boundaries may then be discarded.

10   Reference is now made to FIGURE 5 wherein there is shown a state machine diagram operating the idle ATM cell removal process. The details of the state diagram are described below.

[30] In the HUNT state, the ATM delineation process is

15   performed by checking bit-by-bit for the correct header error control (HEC) field in the cell header. Once it is found, an assumption is made that one header has been found, and the method enters the PRESYNC state. It should be recognized that when byte boundaries are available, the

20   cell delineation process may be performed on a byte-by-byte basis instead.

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[31] In the PRESYNC state, the delineation process is performed by checking cell-by-cell for the correct HEC field. The process repeats until the correct HEC field has been confirmed a certain number (designated DELTA) of times

5   consecutively. As an example, ITU-T I.432 suggests that the DELTA number be 6. The process then moves to the SYNC state. If an incorrect HEC field is found, the process returns to the HUNT state.

[32] In the SYNC state, idle cells will be discarded by

10   checking the header of each cell. The process for performing this discarding operation is shown in the flow diagram of FIGURE 6. The cell delineation will be assumed to be lost if an incorrect HEC field is obtained a certain number (designated ALPHA) of times consecutively. As an

15   example, ITU-T I.432 suggests that the ALPHA number be 7. If an incorrect HEC field is found, the process returns to the HUNT state.

[33] The idle cell discarding operation of FIGURE 6 that is performed in the SYNC state first reads an ATM cell in

20   (step 100). Next, in step 102, the read-in cell is error checked using the HEC field. If the number of error bits exceeds one, as determined in step 104, the process

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performed by the idle cell removal machine will report the
HEC error and return to step 102. Otherwise, the process
moves on to check in step 106 for an idle ATM cell by, for
example, determining whether the virtual path identifier
5   (VPI) virtual channel identifier (VCI) and payload type
(PLT) information bits in the header are all zero, and also
if the cell loss priority (CLP) is one. If not all of
these conditions are met, nothing is to be done with the
read-in cell (step 108) and the process returns to step
10   102. The reason for this is that the process for idle cell
removal is designed to only remove the redundant idle cells
in the ATM data stream. Original data must remain
unchanged. If the ATM cell under examination is not an
idle cell (i.e., the cell is a data cell), the cell is
15   passed on to the next transmitter processing stage. If
there is a match in step 106, the process moves to step 110
where a determination is made as to whether no data exists
to be transmitted on the link. If the determination is no
(i.e., that there is data to be transmitted), then the ATM
20   cell can be discarded in step 112. Otherwise, the ATM cell
is kept in step 114 as a minimum required ATM cell for the
link (for example, for DSL synchronization purposes).

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Following steps 112 or 114, the process returns to step 100
to read in a next ATM cell.

[34] Reference is now once again made to FIGURE 4. The
step 90 determined bit rates for the upstream and

5   downstream will generally be much smaller than the
corresponding maximum available throughput rates of the DSL
loop. This allows for some flexibility to be exercised in
selectively using different parts of the available upstream
and downstream bandwidth to minimize instances of

10   overlapping bandwidth within the same cable bundle that
contributes to NEXT noise and further reduce the power
consumption of the DSL modem. The operation for selective
bandwidth utilization is performed in step 92.

[35] The concept of selective bandwidth utilization (step

15   92) is illustrated in an exemplary fashion in FIGURE 7 for
a CPE DSL receiver. Trapezoid 70 represents the total
available upstream bandwidth. Trapezoid 72 represents the
total available downstream bandwidth. Shaded trapezoid 74
represents the required downstream bandwidth needed to

20   support transmission of the step 90 determined downstream
bit rate for a DSL communication. It is recognized that
the required downstream bandwidth 74 is smaller than the

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total available downstream bandwidth 72. Because of this,
a selective position placement of the required downstream
bandwidth 74 within the total available downstream
bandwidth 72 may be made in step 92. This selective

5   placement is effectuated by sliding (as indicated by the
arrows 76) the required downstream bandwidth 74 in position
along the frequency axis until a suitable location is
identified. The determination of what is suitable is made
in accordance with the present invention by evaluating

10   crosstalk noise at each potential required downstream
bandwidth 74 location within the total available downstream
bandwidth 72. The location chosen for the positioning and
placement of the required downstream bandwidth 74 within
the total available downstream bandwidth 72 is that

15   location where crosstalk noise due to overlapping bandwidth
is minimized.

[36]   It is to be noted here that the meaning of
"overlapping bandwidth" in the context of the present
invention is the bandwidth that is responsible for the

20   existence of crosstalk noise (primarily, NEXT noise) in a
cable bundle. This is graphically illustrated in FIGURES
8 and 9 for two different modes of DSL operation. In

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FIGURE 8, selective bandwidth utilization to minimize NEXT noise is illustrated in a non-overlapped DSL system implementation. A non-overlapped DSL system is one where the upstream and downstream bandwidths are separated from each other in the frequency band. In FIGURE 9, selective bandwidth utilization to minimize NEXT noise is illustrated in an overlapped DSL system implementation. An overlapped DSL system is one where the upstream and downstream bandwidths are not separated from each other (i.e., they wholly or partially overlap) in the frequency band.

[37] Turning first to FIGURE 8, it is noted that on a given cable bundle, M non-overlapped loop communications 80(1)-80(M) already exist. These communications 80 are established and are each using a designated upstream bandwidth 82 and a designated downstream bandwidth 84 on their respective individual loops. Notably, these bandwidths may, and likely will be, of different sizes and positions within the frequency band. At this point, a new loop communication 86 is to be initiated. This loop communication 86, as discussed above in connection with FIGURE 7, has a total available upstream bandwidth 70, a total available downstream bandwidth 72, and a required

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downstream bandwidth 74 that is needed to support transmission of the FIGURE 4, step 90, determined downstream bit rate.

[38] With respect to the DSL receiver for the new loop communication 86, the group of loop communications 80(1)-80(M) and 86 have a NEXT noise overlapping bandwidth 88 extending in the frequency band from f_L to f_H for downstream communications within the cable bundle. The frequency f_L at the low end of the NEXT noise overlapping bandwidth 88 is the lowest frequency for any of the downstream bandwidths 72 or 84 in same cable bundle. The frequency f_H at the high end of the NEXT noise overlapping bandwidth 88 is the highest frequency for any of the upstream bandwidths 70 or 82 in same cable bundle. Noting again that the total available downstream bandwidth 72 is wider than the required downstream bandwidth 74, there exist several (if not many) possible locations where the required downstream bandwidth can be placed within the total available downstream bandwidth. It is further recognized that the NEXT noise contributed to the cable bundle by the addition of the new loop communication 86 and its required downstream bandwidth 74 varies as a function

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of position within the total available downstream bandwidth 72. Theoretically speaking, a best location for the required downstream bandwidth 74 would be completely outside the NEXT noise overlapping bandwidth 88 (for example, in the region designated at reference 116). In most situations, however, due to the relative sizes of the required downstream bandwidth 74 and the total available downstream bandwidth 72, as well as the sizes and positions of the bandwidths 82 and 84, this may not be achievable. However, by sliding the position of the required downstream bandwidth 74 within the total available downstream bandwidth 72 and through the NEXT noise overlapping bandwidth 88 as indicated by the arrows 76, and further noting the NEXT noise contributed to the cable bundle at each possible location, an optimal position having minimized NEXT noise effect may be selected for the required downstream bandwidth 74.

[39] Turning next to FIGURE 9, it is noted that on a given cable bundle, M overlapped loop communications 120(1)-120(M) already exist. These communications 120 are established and are each using a designated upstream bandwidth 122 and a designated downstream bandwidth 124.

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Notably, these bandwidths may, and likely will be, of different sizes, and further overlap each other in whole or in part within the frequency band. At this point, a new loop communication 126 is to be initiated. This loop

5 communication 126, as discussed above in connection with FIGURE 7, has a total available upstream bandwidth 70, a total available downstream bandwidth 72, and a required downstream bandwidth 74 that is needed to support transmission of the FIGURE 4, step 90, determined

10 downstream bit rate. Note, in this scenario, that the total available upstream bandwidth 70 and the total available downstream bandwidth 72 may overlap each other in whole or in part within the frequency band.

[40] With respect to the DSL receiver for the new loop

15 communication 126, the group of loop communications 120(1)-120(M) and 126 have a NEXT noise overlapping bandwidth 128 extending in the frequency band from f_L to f_H for downstream communications within the cable bundle. The frequency f_L at the low end of the NEXT noise overlapping

20 bandwidth 128 is the lowest frequency for any of the downstream bandwidths 72 or 124 in same cable bundle. The frequency f_H at the high end of the NEXT noise overlapping

bandwidth 128 is the highest frequency for any of the upstream bandwidths 70 or 122 in same cable bundle. Noting again that the total available downstream bandwidth 72 is wider than the required downstream bandwidth 74, there

5   exist several (if not many) possible locations where the required downstream bandwidth can be placed within the total available downstream bandwidth. It is further recognized that the NEXT noise contributed to the cable bundle by the addition of the new loop communication 126

10   and its required downstream bandwidth 74 varies as a function of position within the total available downstream bandwidth 72. Theoretically speaking, a best location for the required downstream bandwidth 74 would be completely outside the NEXT noise overlapping bandwidth 128 (for

15   example, in the region designated at reference 116). In most situations, however, due to the relative sizes of the required downstream bandwidth 74 and the total available downstream bandwidth 72, as well as the sizes and positions of the bandwidths 122 and 124, this may not be achievable.

20   However, by sliding the position of the required downstream bandwidth 74 within the total available downstream bandwidth 72 and through the NEXT noise overlapping

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bandwidth 128 as indicated by the arrows 76, and further
noting the NEXT noise contributed to the cable bundle at
each possible location, an optimal position having
minimized NEXT noise effect may be selected for the

5   required downstream bandwidth 74.

[41] Although FIGURES 7-9 illustrate operation of the
selective bandwidth utilization process with respect to a
DSL receiver and the downstream bandwidth, it will be
understood by those skilled in the art that a similar

10   operation may be implemented with respect to positioning
a required upstream bandwidth within a total available
upstream bandwidth as well. It should also be understood
and recognized that the process is equally applicable to
the DSL modem at either end of the cable bundle. The

15   specific reference and illustration in FIGURES 7-9 to
downstream bandwidth is exemplary in nature only.

[42] In order to make the position determinations discussed
above in connection with FIGURES 8 and 9, and execute the
performance of the FIGURE 4, step 92, selective bandwidth

20   utilization process, the NEXT noise at each location, as
the position of the required bandwidth (for example,
reference 74) is slid within the total available bandwidth

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(for example, reference 72), must be computed. The computation of NEXT noise may be accomplished using either of the following two different methods:

[43] First, the Analytical Method. The NEXT noise from n identical disturbing sources can be modeled with empirical coupling transfer functions of the following form:

(1)

$$PSD_{NEXT}(f_k) = PSD_{disturber}(f_k) \times X_N \times n^{0.6} \times f^{\frac{3}{2}}$$

wherein: $X_N = 8.536 \times 10^{-15}$;

n = number of disturbers;

f_k is the frequency in Hz at k-th subcarrier; and

$PSD_{disturber}$ is the power spectrum of the interfering system.

See, T1.417, Spectrum Management for Loop Transmission Systems, American National Standard, Alliance for Telecommunications Industry Solutions (ATIS), January 2001. However, it is very common that different disturbers co-exist in the same cable. To combine the crosstalk contributions from different disturbers, the following

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expression is used to calculate the NEXT noise due to the combination of sources:

(2)

$$PSD_{NEXT\_TOTAL}(f_k) = \left(\sum_{1}^{M} \left(PSD_{i,disturber}(f_k, n_i) \right)^{\frac{1}{0.6}} \right)^{0.6}$$

wherein: M is the number of the types of the
5   disturbers; and

n_i is the number of the disturbing sources for each type.

See, T1.417, Spectrum Management for Loop Transmission Systems, American National Standard, Alliance for
10 Telecommunications Industry Solutions (ATIS), January 2001. For example, consider the case of two sources of NEXT at a given receiver. In this case there are n_1 disturber systems of spectrum $S_1(f)$ and n_2 disturber systems of spectrum $S_2(f)$. The combined NEXT is accordingly expressed
15 as:

$$PSD_{NEXT\_TOTAL}(f_k) = \left(\left(S_1(f_k, n_1) \right)^{\frac{1}{0.6}} + \left(S_2(f_k, n_2) \right)^{\frac{1}{0.6}} \right)^{0.6} \qquad (3)$$

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See, T1.417, Spectrum Management for Loop Transmission Systems, American National Standard, Alliance for Telecommunications Industry Solutions (ATIS), January 2001.

[44]   Second, the Estimation Method. To compute the NEXT noise, an estimate can be made by evaluating the silent symbols during the initialization process. The corresponding equation for this action is as follows:

(4)

$$PSD_{NEXT\_TOTAL}(f_k) = \frac{1}{L\sqrt{2N}} \sum_{i=0}^{L-1} \sum_{n=0}^{2N-1} r_i(n).\exp\left(\frac{j\pi kn}{N}\right)$$

wherein: L is the total number of the silent DMT symbols for the NEXT noise estimation;

i is the index of the subcarriers for NEXT estimation;

N is the maximum number of subcarriers the IDFT modulator can support; and

the value $r_i(n)$ is the n-th received sample for the i-th DMT symbol.

It is to be noted here that this estimation result in fact is the combination of NEXT, FEXT and additive white Gaussian noise. However, as the NEXT noise is the major

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source of interference, the above estimation can be

approximately regarded as the NEXT noise component.

[45]   Reference is now made to FIGURE 10 wherein there

is shown a flow diagram for a process to minimize NEXT

5   noise for the new initialized DSL loop communication in the

same cable bundle in connection with making the position

determinations discussed above in connection with FIGURES

8 and 9, and the execution of the FIGURE 4, step 92,

selective bandwidth utilization process. A loop 156 is

10   executed to make calculations at a plurality of position

locations. For each pass through the loop 156, at step

150, the number of subcarriers needed to support the

upstream data communication and downstream data

communication is found. This step, in effect, calculates

15   the number of subcarriers for each position index i as the

required bandwidth (for example, reference 74) is slid

across the total available bandwidth (for example,

reference 72). This number representing the number of

needed subcarriers is likely to be different at different

20   positions (i.e., locations) of the required bandwidth due

to the fact that different numbers of bits can be supported

in DSL system at different subcarriers. In step 152, the

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total NEXT noise contributed by the required bandwidth at the current position location is determined. This step, in effect, calculates the NEXT noise contribution for each position index i as the required bandwidth (for example,

5   reference 74) is slid across the total available bandwidth (for example, reference 72). This total NEXT noise calculation can be determined in accordance with the following:

(5)

$$P_{NEXT} = \sum_{k=k_1(i)}^{k_2(i)} PSD_{NEXT\_TOTAL}(f_k)$$

10   wherein: k_1 and k_2 are the beginning and ending points of the required bandwidth in terms of the subcarrier index.

It is to be noted here that k_1 and k_2 will depend on the position index i for the subcarriers. The number of

15   subcarriers between $k_1(i)$ and $k_2(i)$ is fully dependent on the upstream/downstream bitmap for the DMT modulator. Finally, in step 154, minimization of the NEXT noise is made by choosing the position index i having the minimum value of P_{NEXT}. The corresponding $k_1(i)$ and $k_2(i)$ values

20   represent the starting and ending subcarriers for the

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required bandwidth (within the total available bandwidth) at the determined position having minimum NEXT noise.

[46]   It should be noted here that NEXT noise minimization process has an added benefit in that the determined $k_1(i)$ and $k_2(i)$ values which represent the starting and ending subcarriers of the required bandwidth at the NEXT noise minimized position within the total available bandwidth further specify, for minimized NEXT noise, a minimum number of subcarriers that are necessary to carry the FIGURE 4, step 90, determined required bit rate for the data communication on the new DSL loop. Minimization of the transmission bandwidth with a smaller number of DMT subcarriers leads to a reduction in the power consumption of the line driver. The DMT signal samples in real form after the IDFT modulation can be expressed as:

(6)

$$s(n) = \sqrt{\frac{2}{N}} \sum_{k=1}^{N-1} g_k \left\{ a_k \cos\left(\frac{\pi kn}{N}\right) + b_k \sin\left(\frac{\pi kn}{N}\right) \right\},$$

wherein: $a_k - jb_k$ is the transmitted data for the k-th sub-carrier;

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N is the maximum number of the subcarriers

the IDFT modulator can support;

2N is the fast Fourier transform size of

the DMT system; and

5   g_k is the transmission power control factor

for the k-th subcarrier.

The average power of the DMT signal can be easily

determined as follows:

(7)

$$P_s^2 = \frac{1}{N} \sum_{k=1}^{N-1} g_k^2 \left(a_k^2 + b_k^2 \right),$$

10   However, if not all of subcarriers are used in the

transmitter, the average power of the DMT signal becomes:

$$P_s^2 = \frac{1}{N} \sum_{k=k_1}^{k_2} g_k^2 \left(a_k^2 + b_k^2 \right),$$ (8)

[47] As the bit rates may vary significantly for different

applications and the data rate across the network has

15   bottlenecks, the operation disclosed above for selective

bandwidth utilization will have a substantial effect on

power consumption reduction. For example, if we assume the downstream bit rate is 500Kb/s, which is typically not available as an Internet accessing speed for most residential users, the power consumption can be reduced by

5   minimizing the number of subcarriers by approximately 91.66% ((6000-500)Kb/6000Kb). Here, we assume a throughput for the DSL downstream of 6Mb/s. For a downstream connection with a lower available accessing speed, this figure can still be higher.

10 [48]   Reference is now once again made to FIGURE 4. Having determined the size and location of the required bandwidth within the total available bandwidth for the new DSL communication, the process generates of the NEXT minimized digital multi-tone (DMT) signal in step 94.

15 [49] The maximum number of the available upstream (U) and downstream (D) subcarriers (S) that can be supported by a DSL modem is denoted as N_{SU} and N_{SD}, respectively. It is noted that N_{SU} and N_{SD} might be different for various DSL standards. It is also noted that not all the available

20 subcarriers are actually used in connection with the implementation of the present invention. The number of the subcarriers actually used for the upstream and downstream

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are accordingly denoted as $N_{upstream}$ and $N_{downstream}$. The $N_{upstream}$ and $N_{downstream}$ subcarriers are determined in the manner set forth above (using the process of step 92 and the determination of the position index i having the NEXT noise

5   minimum value of P_{NEXT} along with the corresponding $k_1(i)$ and $k_2(i)$ values representing the starting and ending subcarriers for the required bandwidth). As also discussed above, the determination of the actual number of subcarriers used is dependent on actual data rate to be

10 transmitted by the DSL modem (upstream and downstream) as determined in step 90.

[50]   Reference is now made to FIGURES 1 and 2 which illustrate functional block diagrams of ATU transmitters for a general DSL modem. The ATU-R transmitter is shown

15 in FIGURE 1 and the ATU-C transmitter is shown in FIGURE 2. The ATU-R transmitter is similar to ATU-C transmitter but without need for and use of an Operation, Administration and Maintenance (OAM) path. The general configuration and operation of such DSL transmitters is

20 well known to those skilled in the art. More detailed discussion of the transmitters is made only to the extent necessary to understand operation of the present invention.

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The operations of steps 90 and 92 as set forth in Figure 4 may be performed by the Mux/Sync Control/Idle Cell Removal machine 196 within FIGURES 1 and 2.

[51] Reference is now made in combination to FIGURES 1, 2 and 4. The generation of the NEXT minimized DSL signal in step 94 is realized through inverse Discrete Fourier Transform (IDFT) modulation (reference 190). The modulating transformation that defines the relationship between the real time domain samples x_n (i.e., the DSL output signals) and the IDFT input Z_i' (to be discussed below) is given by:

(9)

$$x_n = \sum_{i=0}^{2N-1} \exp\left(\frac{j\pi ni}{N}\right) Z_i'$$

wherein: n = 0,..., 2N-1;

N is a general symbol for the maximum number of the subcarriers supported by the modem (either N_{SU} or N_{SD}); and

i denotes the subcarrier whose real time domain samples x_n are being calculated.

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The result x_n is the signal to be transmitted on the new DSL loop 192. When the steps 90 and 92 are performed by the ATM idle cell removal machine within the MUX/Sync/Idle Cell Remove block 196 in FIGURES 1 and 2 of the transmitter

5   model, the output x_n from the IDFT modulator 190 should generate less NEXT noise to other users in the cable bundle and be power reduced.

[52] For ATU-R (residential or CPE location) and ATU-C (CO location) transmitters, Z_i' is generated using different

10   methods as discussed in more detail below.

[53] For an ATU-R transmitter, assume that $N_{upstream}$ subcarriers $(k_1(i), k_1(i) + 1, \ldots, k_2(i)$, where $k_2(i) = k_1(i) + N_{upstream} - 1)$ are allocated for the transmission of an upstream signal for a given bit rate. The relationship

15   between $k_1(i)$, $k_2(i)$, and N_{SU} are: $k_1(i) \geq 1$ and $N_{SU} > k_2(i) > k_1(i)$. It should be noted, for the convenience of this discussion, that it is assumed that the $N_{upstream}$ subcarriers are continuous subcarriers in frequency domain, but this is not a necessity. The complex values from the

20   constellation encoder and gain scaling (reference 194) for the i-th subcarrier is Z_i (i.e., the input data to be transmitted, already packed into symbols). In order to

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generate the real output x_n from the IDFT modulation as set forth above, Z_i is first mapped to Z_i' using:

(10)

$$Z_i' = \begin{cases} 0 & 0 \le i < k_1(i) \\ Z_i & k_1(i) \le i \le k_2(i) \\ 0 & k_2(i) + 1 \le i \le N_{SU} \end{cases}$$

The vector Z_i' shall be augmented such that Z_i' has the Hermitian symmetry as follows:

$$Z_i' = conj\left(Z'_{(2N_{SU}-i)}\right)$$

(11)

for i = N_{SU} + 1 to $2N_{SU}$ - 1.

Equation (9) is then used by reference 190 to generate the real output x_n from vector Z_i'.

[54] For an ATU-C transmitter, assume $N_{downstream}$ subcarriers $(k_1(i), k_1(i) + 1, \ldots, k_2(i)$, wherein $k_2(i) = k_1(i) + N_{downstream} - 1)$ are allocated for the transmission of the downstream signal for a given rate. The relationship between $k_1(i)$, $k_2(i)$, N_{SU} and N_{SD} are: $k_1(i) \ge N_{SU} + 1$; and $N_{SD} > k_2(i) > k_1(i)$.

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As we mentioned earlier, the $N_{downstream}$ subcarriers allocated to the downstream need not necessarily be continuous. A non-overlapped spectrum is assumed in the DSL system operation for this discussion. In the overlapped mode, the generation of the DSL downstream signal is similar to the upstream. In order to generate real output x_n from IDFT modulation (as discussed above), Z_i is first mapped to Z_i' using:

(12)

$$Z_i' = \begin{cases} 0 & 0 \leq i < k_1(i) \\ Z_i & k_1(i) \leq i \leq k_2(i) \\ 0 & k_2(i) + 1 \leq i \leq N_{SD} \end{cases}$$

The vector Z_i' shall be augmented such that Z_i' has Hermitian symmetry as follows:

$$Z_i' = conj\left(Z_{(2N_{SD}-i)}\right)$$

for i = N_{SD} + 1 to $2N_{SD}$ - 1.
(13)

Equation (9) is then used by reference 190 to generate the real output x_n from vector Z_i'.

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[55]   Although preferred embodiments of the method and apparatus of the present invention have been illustrated in the accompanying Drawings and described in the foregoing Detailed Description, it will be understood that the invention is not limited to the embodiments disclosed, but is capable of numerous rearrangements, modifications and substitutions without departing from the spirit of the invention as set forth and defined by the following claims.

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